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ABSTRACT

We present a new diagnostic for the National Ignition Facility (NIF) [1,2]. The Streaked Polar Instrumentation for Diagnosing Energetic Radiation (SPIDER) is an x-ray streak camera for use on almost-igniting targets, up to ~10^{17} neutrons per shot. It measures the x-ray burn history for ignition campaigns with the following requirements: X-Ray Energy 8-30keV, Temporal Resolution 10ps, Absolute Timing Resolution 30ps, Neutron Yield: 10^{14} to 10^{17}. The features of the design are a heavily shielded instrument enclosure outside the target chamber, remote location of the neutron and EMP sensitive components, a precise laser pulse comb fiducial timing system and fast streaking electronics. SPIDER has been characterized for sweep linearity, dynamic range, temporal and spatial resolution. Preliminary DT implosion data shows the functionality of the instrument and provides an illustration of the method of burn history extraction.

Keywords: National Ignition Facility (NIF), inertial confinement fusion (ICF), streak camera, x-ray diagnostics, neutron mitigation, SPIDER, bang time, burn width

1. INTRODUCTION

Measurement of the absolute time (bang time) and burn width of the peak x-ray emission from the imploding cores of deuterium-tritium capsules near peak compression is integral to the success of the ignition campaign [3,4]. These measurements are used to validate implosion modeling and confirm the symmetry tuning parameters of the laser as well as the DT capsule. The challenge for x-ray diagnostics in inertial confinement fusion (ICF) experiments is to not only withstand the damage from an intense flux of energetic neutrons, but also to minimize the detrimental signal contribution from these neutrons, electromagnetic impulses and background x-rays. The SPIDER was specifically designed to measure the x-ray bang time and burn width in a neutron yield of up to 5×10^{16} at target chamber center (TCC). It manages to achieve this by enclosing the instrument in heavy shielding, positioning the instrument several meters away outside the target chamber, and temporally gating the micro-channel plate.

SPIDER has recently been commissioned at NIF and has been run on several shots. Preliminary implosion data is very promising and clearly illustrates the capabilities of the SPIDER. The next section describes the design and architecture of the instrument. Section three reports the performance of SPIDER as determined by a series of standardized calibration procedures. Section four defines the process of extracting the implosion signal from the hohlraum emission background.

2. DESIGN

The architecture of the SPIDER is motivated by neutron mitigation while maintaining high precision. The drawings of the general arrangement of the instrument (figures 1 and 2) emphasizes the additional shielding, line of sight (LOS) of the instrument, the distance of the instrument from TCC, and the separate vacuum system. The platform holding the SPIDER cart is composed of two 1" steel plates and 12" of high-density polyethylene (HDPE) in between the plates. Additionally, there is an air gap in the beam line from the LOS tube to the SPIDER cart. The LOS tube is capped with a 5mm thick polyimide window which prevents the target chamber from venting due to debris hitting the window. Unfortunately, this greatly reduces the instruments response for x-rays below 10keV. There is a plan to replace this with an appropriately thick beryllium window once beryllium is allowed for use in the target chamber. One of the most important features of SPIDER is the 30° angle of incidence of the LOS with respect to the axis of the instrument; it prevents neutrons and hard x-ray signals from directly interacting with the CCD and streak tube. Another essential aspect of the instrument is the long distance from the slit to the TCC. At ~9200 mm, the difference between the time of flight between x-rays and 14 MeV neutrons is about 150 ns, which ensures that the neutron signal does not interfere with the x-ray implosion emission signal. The field of view of SPIDER is a circle with a diameter of about 150mm at TCC.

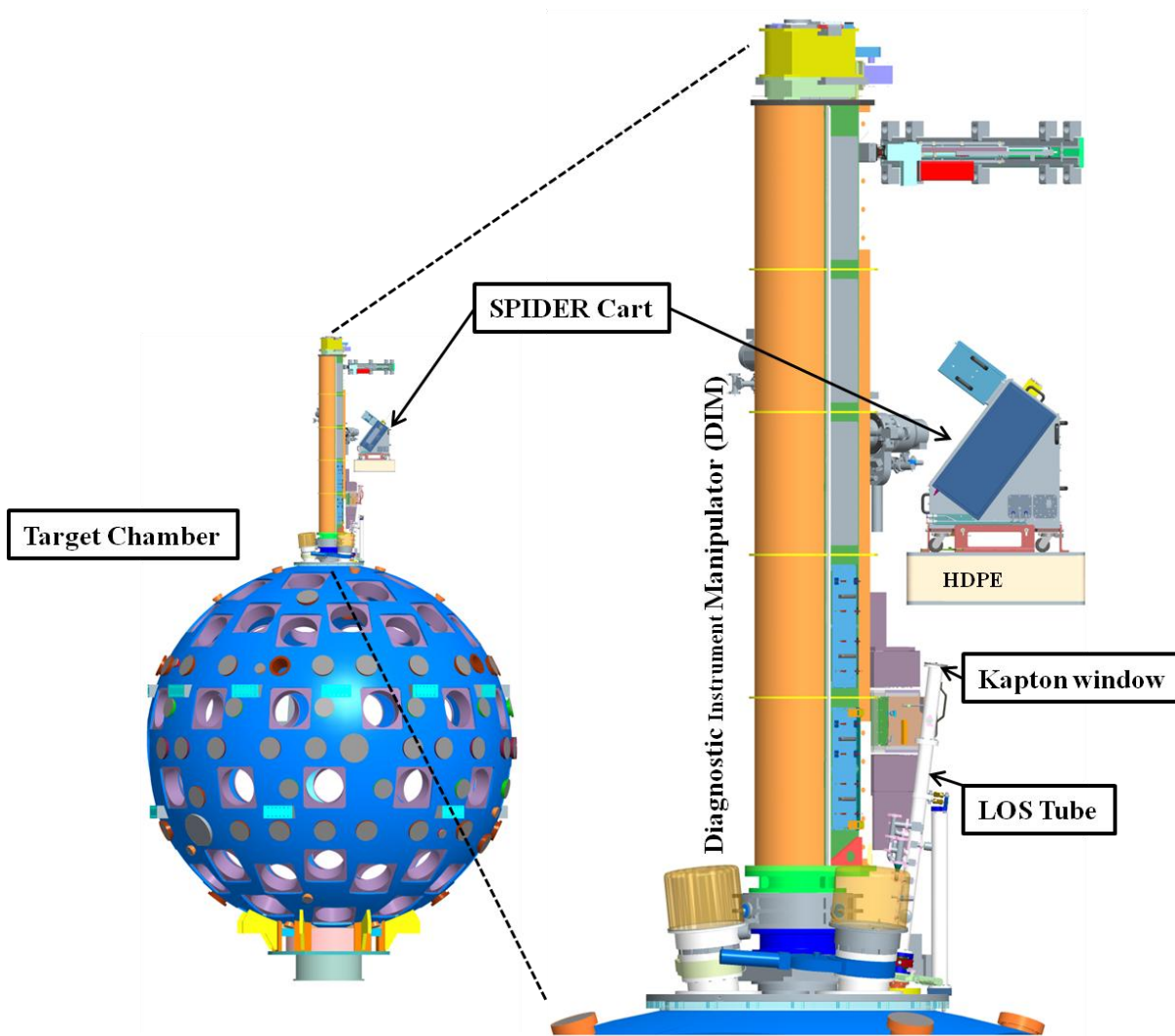Figure 1. Model of the NIF target chamber, Polar Diagnostic Instrument Manipulator (DIM), SPIDER cart, and LOS tube. Note the large distance between SPIDER and TCC (~9235 mm). The platform holding SPIDER is composed of two 1" steel plates and 12" of high-density polyethylene (HDPE). The SPIDER axis is at a 30° angle of incidence with respect to the LOS. The field of view as seen by SPIDER at TCC is ~150mm wide.

Figure 2, below, shows the SPIDER cart in detail. The cart has an independent vacuum pumping system and there is a 1mm polyimide window for the x-ray signal. This design isolates the target chamber vacuum system from that of the SPIDER. Several inches of tungsten line the front and sides of the housing to shield the instrument from neutrons and gamma rays. Thick HDPE material is used as additional neutron shielding and placed on the bottom and sides of the cart. A set of filters allows for the study of the spectral properties of the x-ray emission. The current design uses three filters: 33µm Zinc, 14µm Aluminum and 11µm Niobium. The resulting recorded filtered SPIDER signal is shown in figure 6.
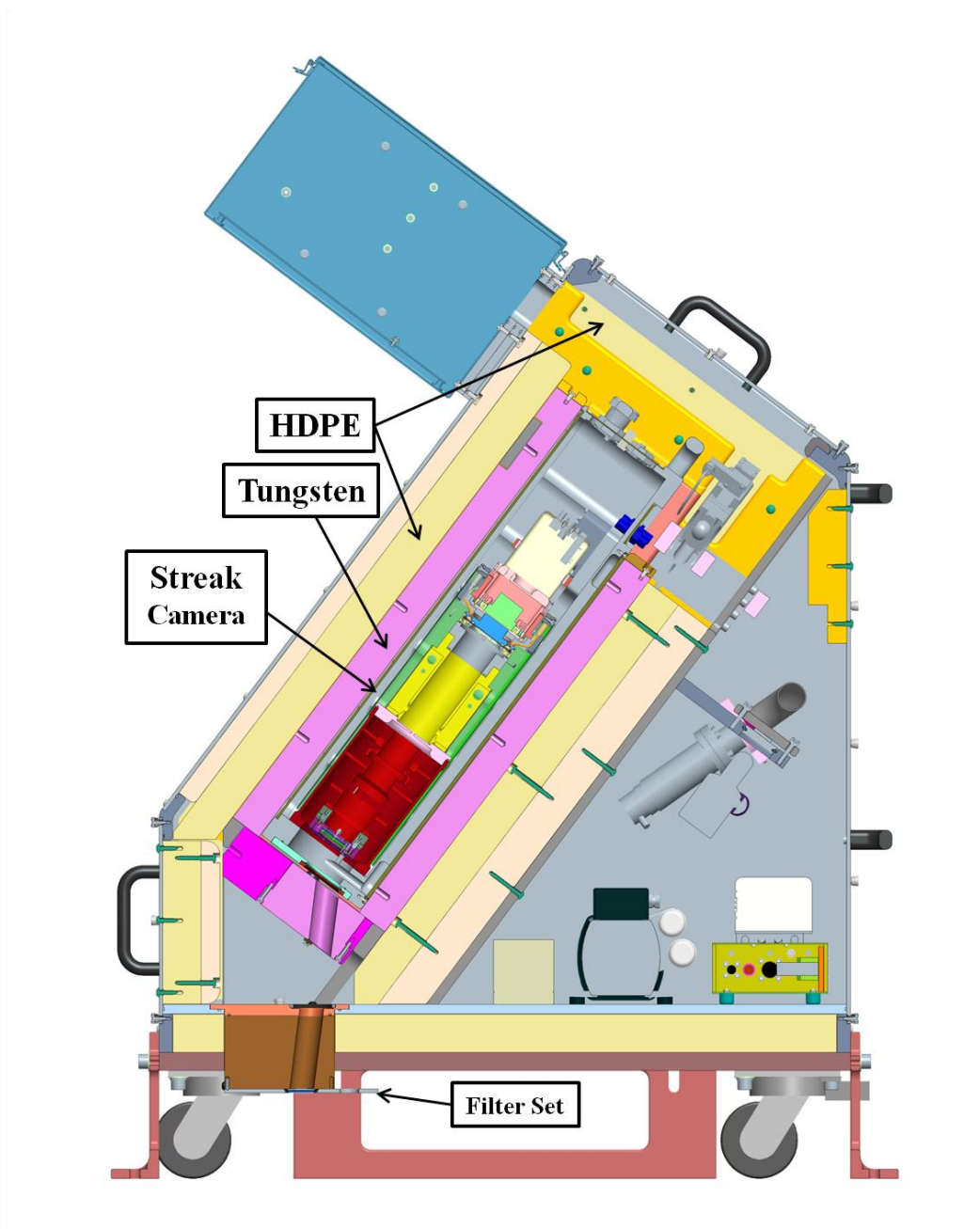

Figure 2. Cross-section of the SPIDER cart showing the shielding employed. Thick Tungsten metal (pink colored) surrounds the front and sides of the aluminum housing followed by high-density polyethylene (cream colored).

The SPIDER recording system is built inside an aluminum housing similar to the DIM Imaging Streak Camera (DISC) [5,6] currently fielded at the NIF. Figure 3 shows the main components of the SPIDER: the photocathode/slit assembly, the Kentech supplied electron optics and sweep assembly, the image intensifier assembly (micro-channel plate/phosphor), and the CCD camera. The photocathode assembly consists of a 250 μm slit that is angled by 30° about the horizontal diagonal of the beam path so that any direct LOS x-ray signal is not imaged by the phosphor and CCD camera. The photocathode consists of two materials deposited side by side onto a 1000 Å Lexan substrate: x-rays are converted to photoelectrons with 2000Å of CsI that is deposited onto a 300 Å Au conductive layer, the other section utilizes 500Å of Al which is devoted to converting the 263 nm fiducial comb pulses into electrons [6]. The final component of the photocathode assembly is a mesh, used to apply a high voltage gradient needed to accelerate the photoelectrons past a set of electrostatic focusing lenses and deflection plates onto the intensifier assembly. The focusing lenses introduce a~1.2-1.3X internal magnification. The sweep assembly consists of a pair of deflection plates driven by a ~1.2 kV voltage ramp. A bias voltage can be applied to either plate in between -1kV to 1kV in order to adjust the position of the swept image in the focal plane. The image intensifier assembly consists of a MCP coupled to a phosphor coated fiber optic face plate. The MCP pores have a length to diameter ratio (L/D) of 46:1, an open area ratio of 60% and a bias angle of 8°. There are three possible MCP gain settings: Low ~ 650V, Medium ~ 750V, and High ~ 850V. The usual setting is medium due to a good balance of signal to noise and dynamic range of the instrument. The phosphor coating on the 40 mm length fiber optic faceplate is the P43 type, which produces 545nm light. The downside to this phosphor type is the slow extinction of about 1.5ms. In order to reduce the contribution of the neutron background signal, the MCP and gating electronics were built with a fast shunt to ground of about 10ns. The CCD camera is a Spectral Instruments SI-1000 model with a Kodak KAF16801E, Front Illuminated, 4096 x 4096, 9μm pixel, full frame CCD [7]. The CCD is thermoelectrically cooled to -20°C which nominally produces dark current at a rate of 0.05e-/pixel/s.
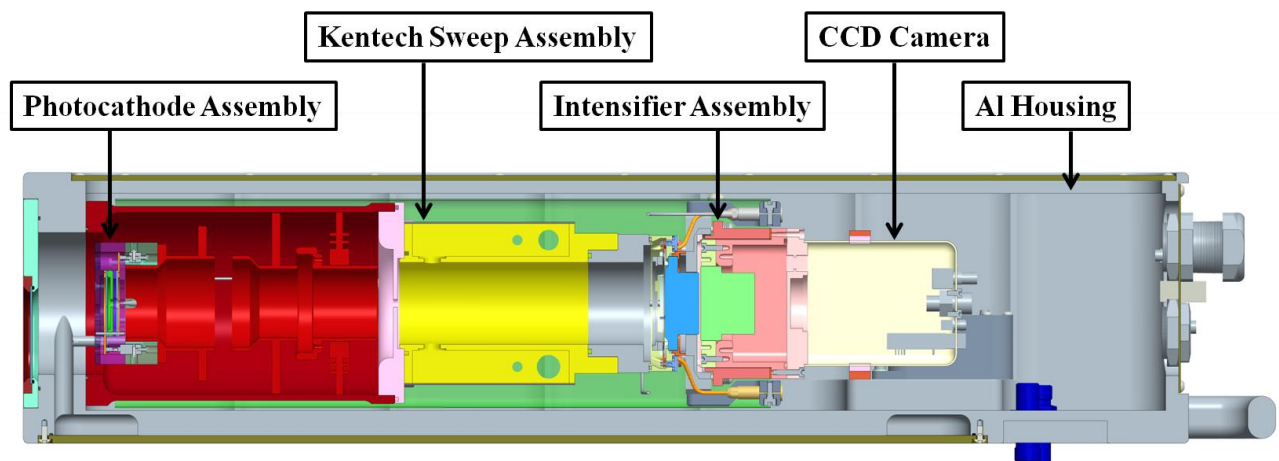

Figure 3. The main components of the SPIDER are shown as situated inside the aluminum housing. From left to right: the photocathode and slit assembly, the Kentech streak tube assembly, the image intensifier assembly, and the CCD camera.

In order to precisely measure the bang time (BT) and burn width (BW) of the capsule implosion, a comb of 45 ps FWHM pulses are used to determine the time scale of the x-ray streak image [8]. The pulse comb appears as a series of six spots on the left edge of the image that spans 1.5ns. The pulses are produced by siphoning a small percentage of the NIF seed laser, then splitting the pulse with a fiber optic splitter, then temporally delaying each pulse by sending the pulse through different length fiber optic cables [6,9]. The pulses are frequency quadrupled to 263 nm using two second harmonic crystals. This frequency conversion along with further amplification occurs inside a separate aluminum housing that is attached to the SPIDER cart (not shown). The fiducial system has been successfully tested with SPIDER off line and implemented on DISC, illustrating an absolute timing accuracy of 4-5ps.

3. PERFORMANCE CHARACTERISTICS

3.1 Calibration

Before fielding the instrument, the performance and characteristics of the instrument were determined by a series of measurements and calibrations. The characterization method is the standardized procedure used for the DISC and other streak cameras at NIF [10, 11], and measures the spatial resolution, temporal resolution, dynamic range, sweep linearity, and spatial uniformity (flat-field) of SPIDER. A summary of the results of this characterization is presented in Table 1 for the sweep settings we will use: 1.5ns, 2ns, 3ns, 5ns. For each sweep window setting, the actual sweep window depends on the detailed as-built streak electronics and the actual separation from the deflector plates and the image intensifier. The spatial resolution is a measure of the minimum feature that can be distinguished in the spatial direction. The 1.5 ns setting produced low counts which accounts for the larger value and uncertainty. The temporal resolution is determined by the size of the slit in front of the photocathode and shortens for smaller sweep windows. The 5th column shows the level of CCD counts where a pulse shorter than the temporal resolution broadens by 20%. Since this effect is mostly dependent on the space charge repulsion in the focusing part of the tube and not on the sweeping part, the levels for the different sweep settings are very close. The sweep linearity and flat-field data cannot be shown in tabular form, but examples of these are given in ref [10, 12]. Warping of the image arises from the cylindrical electron optics between the photocathode and the image intensifier. This effect from the electron optics is for the most part, reproducible and correctable. The sweep linearity is measured in order to develop a time history correction to the streak image. The spatial uniformity is measured by taking a slow sweep across the CCD with a uniform flat in time x-ray source. This test allows for the creation of a flat-field correction image that mitigates the contribution from non-uniformities in the MCP and phosphor coated fiber optic face plate.

Table 1. Measured characteristics of the SPIDER.

Sweep Speed Setting, ns	Measured sweep window, ns	Spatial Resolution, μm	Temporal Resolution, ps	Broadening Limit (medium gain), CCD counts
1.5	1.345	139 ± 37	8.1	3380 ± 500
2	1.849	98 ± 4	12.6	3800 ± 500
3	2.626	104 ± 12	19.1	4200 ± 500
5	4.542	109 ± 24	34.6	3600 ± 500

3.2 Neutron Effects

The effects of neutrons on the SPIDER were carefully investigated in order to design adequate shielding and predict the neutron yield limits for which the instrument can continue to measure the x-ray burn history within the specified tolerance. Simulations of the neutron and photon flux at both the photocathode and the CCD were done using the general Monte Carlo N-Particle (MCNP) transport code [13]. Figure 4 shows plots of the simulated neutron (left plot) and the gamma ray (right plot) per MeV per source neutron at the CCD position for two cases: no SPIDER shielding and current SPIDER shielding configuration. The simulations show that the current shielding configuration reduces the 14 MeV neutron flux by a factor of 33 and the integrated neutron flux by 25. The gamma ray contribution is reduced by an order of magnitude. The CCD degradation due to saturated pixels is proportional to the amount of energy deposited in the silicon. For a neutron yield of 10^{16}, the integrated deposited energy with shielding is calculated to be 0.0045 rad(Si) from neutrons and 0.025 rad(Si) from gamma rays. Figure 5 shows the simulated images [14] of an ideal capsule emission with neutron background noise: 10^{16} neutron yield (left) and 10^{17} neutron yield (right). The simulated images imply that with the current shielding configuration, SPIDER will still be able to report accurate BW and BT values. In the 10^{16} neutron yield case the signal to noise ratio (S/N) is ~7.5 whereas in the 10^{17} neutron yield case the S/N is ~0.7. Averaging over all the rows of data will significantly reduce the effects of the high energy radiation induced background. Measurement of the BT and BW on the noisy data and comparing with the clean simulation indicates that the neutron-induced noise contribution will generate an uncertainty of the measurement of the BT & BW of ~5ps.
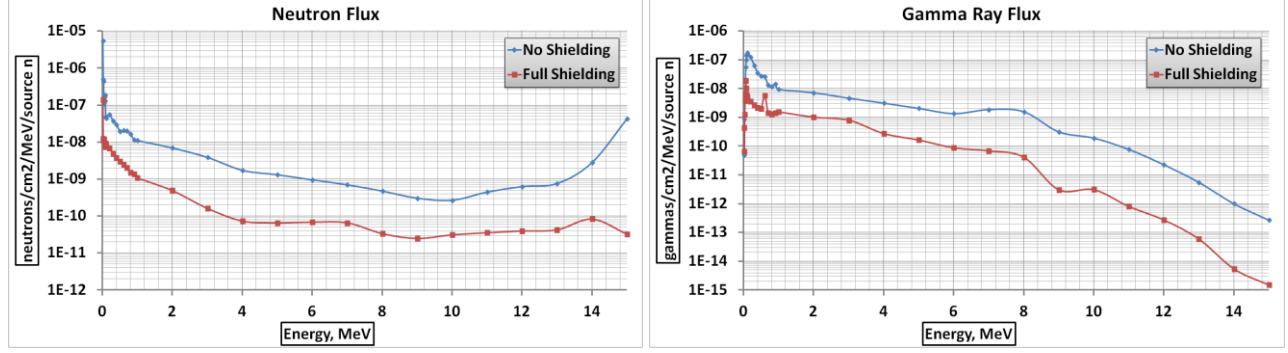
Figure 4. Left: Plot of simulated neutron per MeV per source neutron at the CCD position with and without the current SPIDER shielding. Right: Plot of simulated gamma ray per MeV per source neutron at the CCD position with and without the current SPIDER shielding. The simulations were done using the MCNP code. The shielding reduces the integrated neutron flux by a factor of ~25.
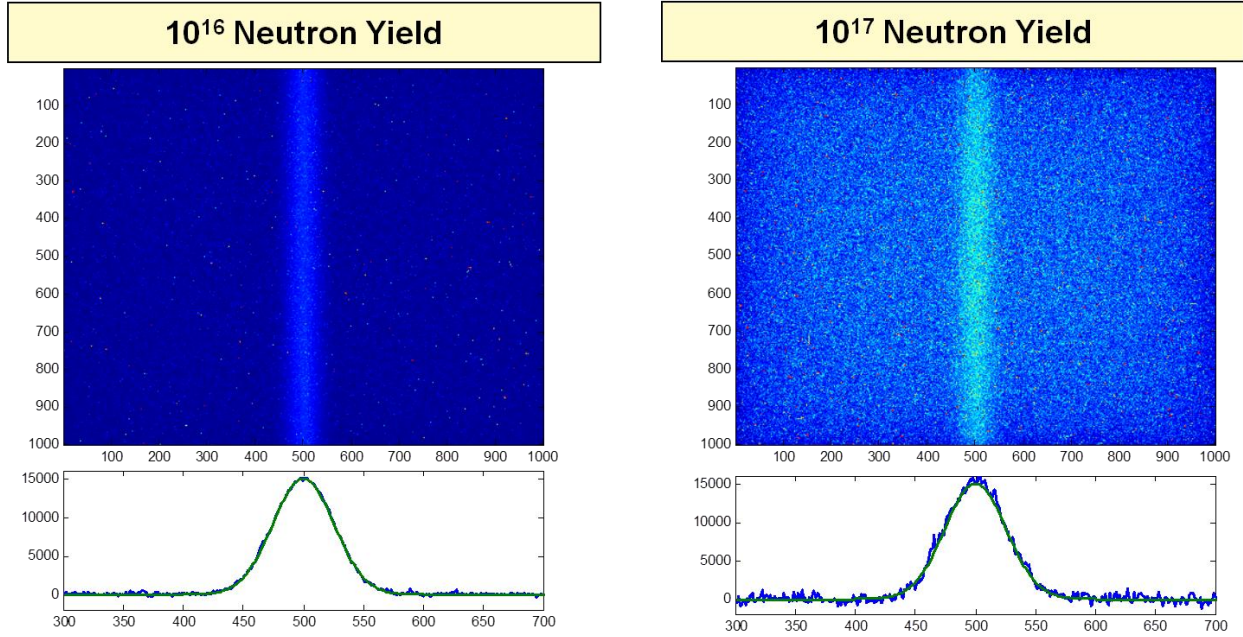

Figure 5. Simulated images of capsule emission with neutron background noise for 10^{16} neutron yield on the left and 10^{17} neutron yield on the right. The x-ray emission is scaled to what is expected for these yield levels.

4. INITIAL RESULTS FROM THE NIF

A series of recent implosion experiments exemplifies the capabilities of SPIDER. The instrument sees both the x-ray emission from the hohlraum as well as that from the imploding capsule. Figure 6 shows the streak image from a recent implosion experiment at the NIF. Time flows from bottom to top and the total duration of the streak on this image is ~4.5ns. In order to extract the BW and BT of the implosion, the following procedure is used. First, the hohlraum emission is modeled by an exponentially decaying function of the form

$$a_0 + b_0 e^{-\frac{t-b_1}{b_3}} + c_0 e^{-\frac{t-c_1}{c_3}} \ . \tag{1}$$

After removing the hohlraum emission contribution from the signal, the remaining signal is fitted to a Gaussian function in order to retrieve the width and offset. These steps are illustrated in Figure 7. In this particular DT shot, SPIDER measured an x-ray burn width of ~168 ± 12ps and a bang time of ~24.17 ± 0.022ns. These values are within the range of results reported by the other x-ray diagnostic instruments that reports BT and/or BW.
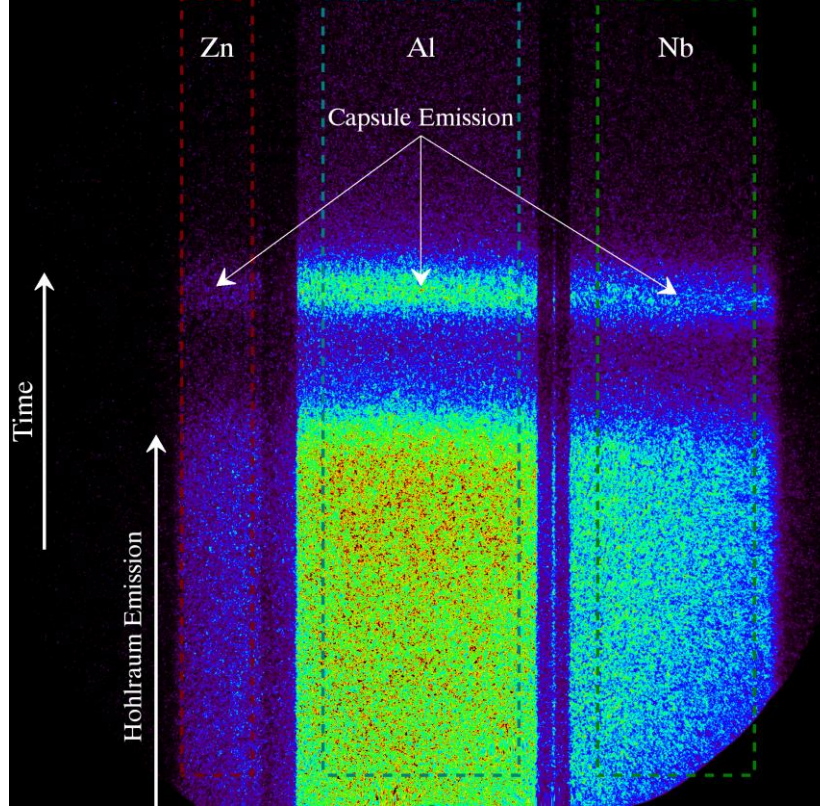

Figure 6. The streak image from SPIDER shows the hohlraum emission and the capsule emission. Time flows from bottom to top and the streak duration on the camera is 4.54 ns long. The SPIDER was fielded with a set of three filters for spectral binning: 33μm Zinc, 14μm Aluminum and 11μm Niobium.
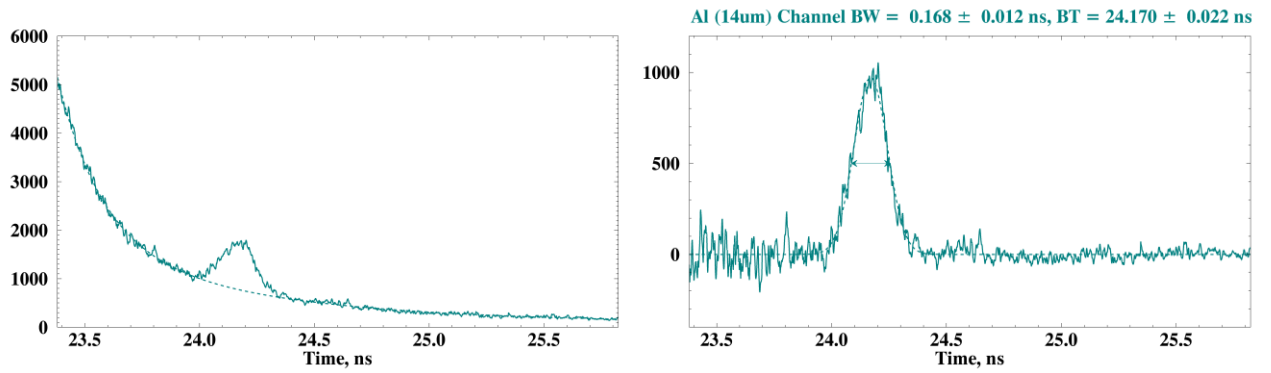

Figure 7. Left: Plot of the average of the columns within the Al filter. The dashed line indicates the exponential fit. Right: Gaussian fit of the extracted capsule emission showing a resulting burn width of ~168 ps and a bang time of ~24.17 ns.

5. CONCLUSION

SPIDER is a high resolution burn history diagnostic that has been fielded on implosion shots at the NIF. The SPIDER was built to operate in a high TCC neutron environment of 5×10^{16} into $4\pi r^2$. This was accomplished by heavy shielding, complex electronics and an integrated design. Simulations of the effects of neutrons and gamma rays on SPIDER determined the shielding configuration and set the operating limits for reporting burn width and bang time within specifications. Characterization of the instrument showed that the instrument performed within the temporal resolution specifications. The sweep linearity and the flat field measurements provided correction data that are currently applied to the NIF experimental data. A simple signal extraction technique is employed in order to report the burn width and bang time of the imploding capsule. Preliminary results indicate that the instrument is capable of recording the burn history of imploding capsules with the accuracy required by the ignition campaign.

6. ACKNOWLEDGEMENT

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